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UNCLASSIFIED TITLE A GEOMETRICAL ANALYSIS OF THE SEATED HUMAN BODY FOR USE IN RADIATION DOSAGE CALCULATIONS

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INTRODUCTION

The particular problem treated in this document is the determination of the thickness of material that must be traversed by incident radiation coming from every direction if it is to reach a particular body-interior point. Specifically, we have calculated the fractional solid angle subtended, around each of twelve body points, by various tissue thicknesses. As a part of this calculation, contours of "isothickness" are given for a seated 75-percentile man. The tables of fractional solid angle vs. tissue thickness are directly useful in computing a body point dose in an isotropic radiation flux. The contours of constant tissue thickness are needed to compute numerically the body point dose in a known non-isotropic radiation field. Coupled with the detailed design of a spacecraft, the dose to these specific body points from a given incident radiation could be calculated. This larger dose computation problem has been programmed for IBM 7090 for incident protons and electrons of arbitrary typical spectra, and will be reported elsewhere (Ref. 1).

METHOD OF COMPUTATION

The determination of the isothickness contours, and the computation of fractional solid angle, are both straightforward. The methods are essentially those of descriptive geometry, in which the human body is carefully drawn in three views, and tissue thicknesses are measured in all directions around the body point of interest.

As a representative human shape, presumably of interest in the astronautics problem, the seated 75-percentile male body was chosen. All dimensions were those given by Hertzberg, Daniels, and Churchill (Ref. 2), who measured the sizes of body structures of a statistical number of Air Force men. The "75-percentile man" is the composite man whose measurements were larger than 75 percent of all the men studied. In the significant sizes*, such as trunk thickness, chest width, etc., the 75-percentile man is usually about a centimeter larger than the mean. These 75-percentile measurements were used as the basis for outline and section drawings of a seated man. Along with these objective data, in order to arrive at realistic figures, cross sectional anatomy data was used (Ref. 3). Thus, a series of sectional views of the hypothetical man was drawn; first, horizontal plane sections, and from them, vertical plane sections containing the point of interest in the body.

In any of the accurately drawn vertical plane sections, a line from the body point of interest to the body surface can be measured to give the tissue thickness (the "true length" in descriptive geometry terms) along the

* That is, significant for radiation dose calculation.

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particular direction of that line. A series of such lines for selected thickness were drawn for six or eight vertical sections at various angles from the front. ("Vertical" is here defined as the direction of the trunk axis if the man were seated erect in a normal chair and room. "Horizontal" is defined by the plane perpendicular to the vertical.)

Two angles are needed to define a thickness line, a "latitude", or angle from the "horizontal" plane to the line, and a "longitude", or angle from the front to the line. Figure 1 illustrates these definitions for the case of a point in the gut region of our hypothetical 75-percentile seated man. Using care to draw these longitudinal cross section views of the human body, and to measure a large number of thicknesses, x, at various θ and ϕ values, one acquires data for thickness contours. Actually, a series of thicknesses was chosen and θ values found on given ϕ sectional views. This data readily plots into isothickness contours. Figure 2 is a plot of these contours on a θ, ϕ map for the gut point of Fig. 1. With a little imagination, one can identify some body structures as seen from this gut point looking out in all directions.* Shoulders, legs, etc. are clear; other parts are less obvious. In Fig. 2 the body was assumed to be composed entirely of soft tissue; the bones and lungs were neglected insofar as they are different from tissue. The effects of lungs and bone are discussed later.

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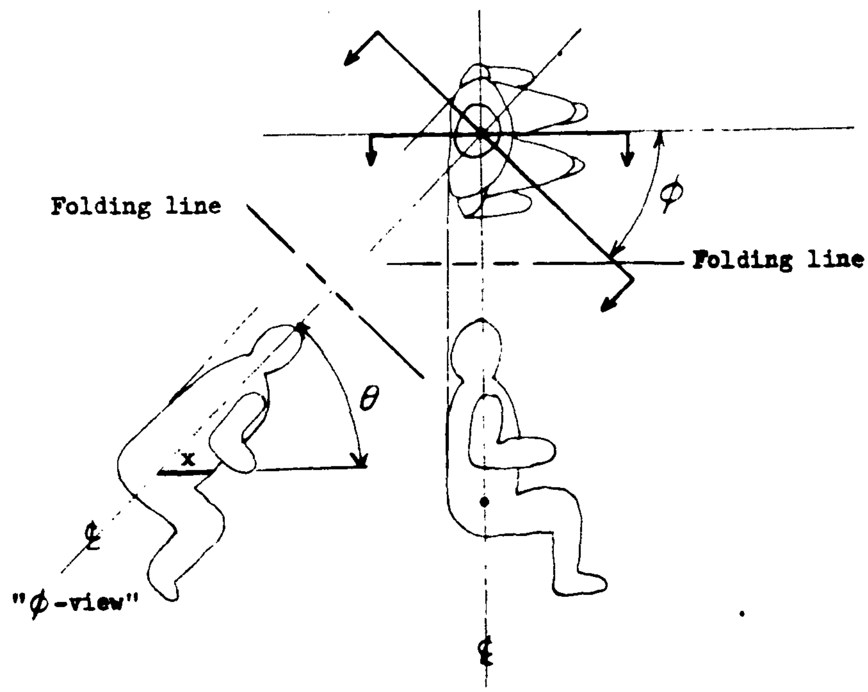
* This might be considered the inverse process of omphaloscepsis!



℄ is vertical axis, passing through the point of interest (Gut).

ϕ is longitude angle.

θ is latitude angle.

x is thickness, a function of θ and ϕ for this point.

FIGURE 1. A few views and sections used in determining thickness of tissue around a point in the gut.

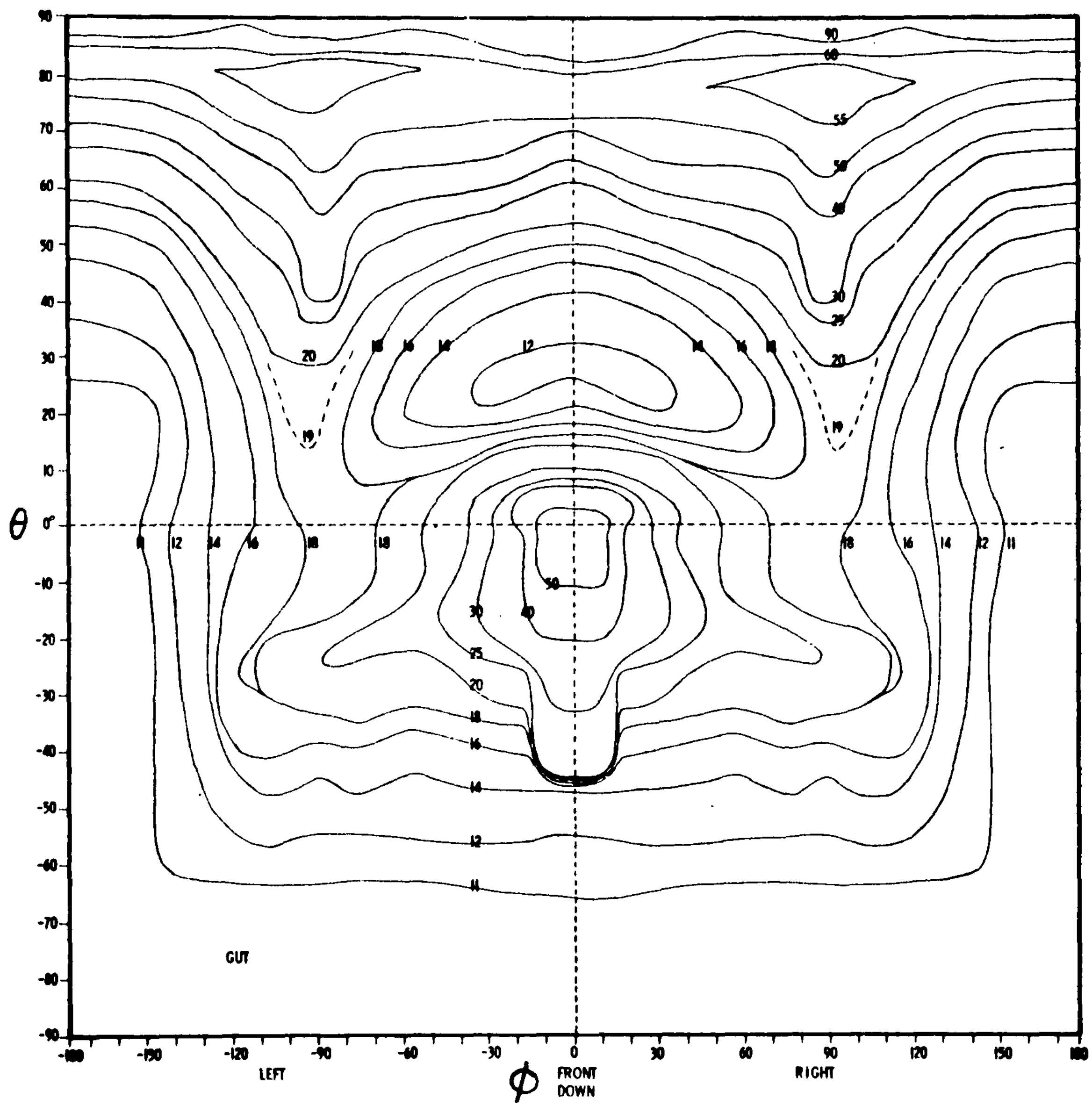


FIGURE 2. Contour plot of tissue isothicknesses in all directions about the point, GUT, located as indicated in Table 1, in a seated 75-percentile man. $\theta = 0$, $\phi = 0$, center of the figure, is the straight ahead horizontal direction.

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ISOTHICKNESS CONTOURS FOR VARIOUS BODY POINTS OF RADIOBIOLOGICAL INTEREST

Twelve points in the assumed seated 75-percentile man were selected for this study. Some of these points are of specific radiobiological interest, since body radiation responses are associated with organs situated there. In this category are gut, sternum, femur, spleen, and eye lens. Others of the selected points allow an estimate of trunk depth dose distribution. For some points the effect of considering bone or lung air was found for the isothickness contours. Table 1 summarizes the chosen points, and gives an identifying code symbol. Using the methods illustrated in Fig. 1, mappings were made of lines of constant tissue thickness between the body surface and the selected points. Nine such contours are shown in Figs.2 through 10 for gut, chest skin, sternum (with air in the lungs), femur (neglecting bone), eye lens, waist skin, waist 4 cm deep, waist 8 cm deep, and spinal column, respectively. Latitude θ is plotted vertically, longitude ϕ horizontally; thus the head is along the top in the isothickness contours for body trunk points, the body front is on the center, and the back is along the edges, where -180° is the same as +180°.

TABLE 1. Description of Body Points Analyzed.

Body Point	Symbol
Central Gut, 10 cm up from seat, and 10 cm forward from back of seat.	GUT
Chest Center, on the skin surface, 55 cm up from seat.	CHEST 0
Chest Center, 2 cm in from the skin, in sternum, 55 cm up from seat, neglecting lungs.	CHEST 2
Chest Center, 2 cm deep, in sternum, as before, taking account of air in lungs.	CHEST 2 L
Spinal Cord Region, 55 cm up from seat, 2 cm deep in body.	BACK 2
Femur, that is, leg center, 38 cm forward from back of seat, 9 cm up from seat level (neglecting bone).	FEMUR
Femur, same point as before, taking account of bone structure (See Text).	FEMUR B
Eye lens, right eye surface, neglecting facial and cranial bony structure.	EYE
Waist, right side, on the skin, 25 cm up from seat level.	WAIST 0
Waist, right side, 25 cm up from seat level, 1 cm in from skin, on the mid-saggital line.	WAIST 1
Waist, right side, 25 cm up from seat level, 4 cm in from skin, on the mid-saggital line.	WAIST 4
Waist, right side, 25 cm up from seat level, 6 cm in from skin, on the mid-saggital line.	WAIST 6
Waist, right side, 25 cm up from seat level, 8 cm in from skin, on the mid-saggital line.	WAIST 8

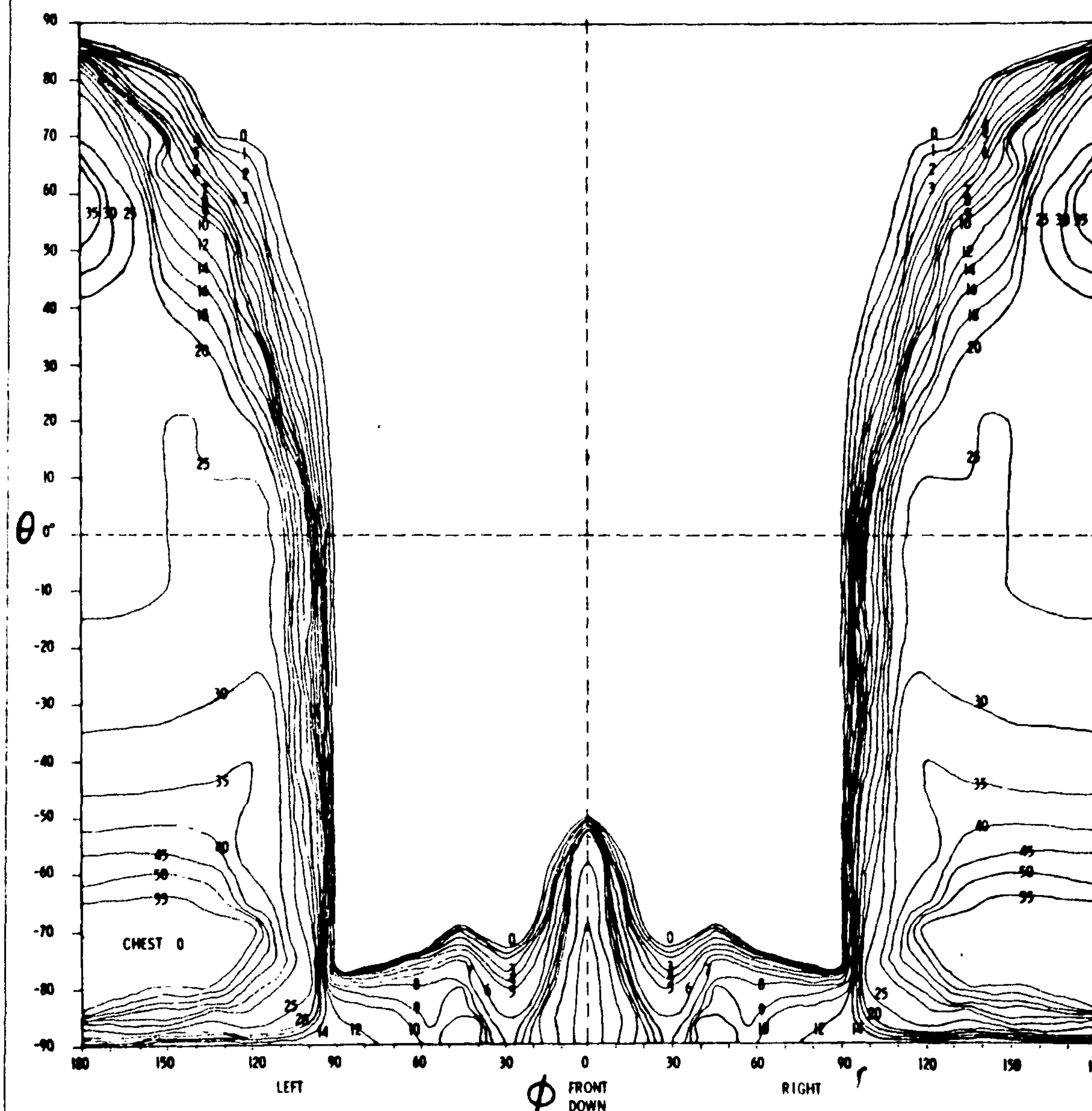

FIGURE 3. Contour plot of tissue isothicknesses in all directions about the point, CHEST 0, located as indicated in Table 1, in a seated 75-percentile man. θ = 0, ϕ = 0, center of figure, is the straight ahead horizontal direction.

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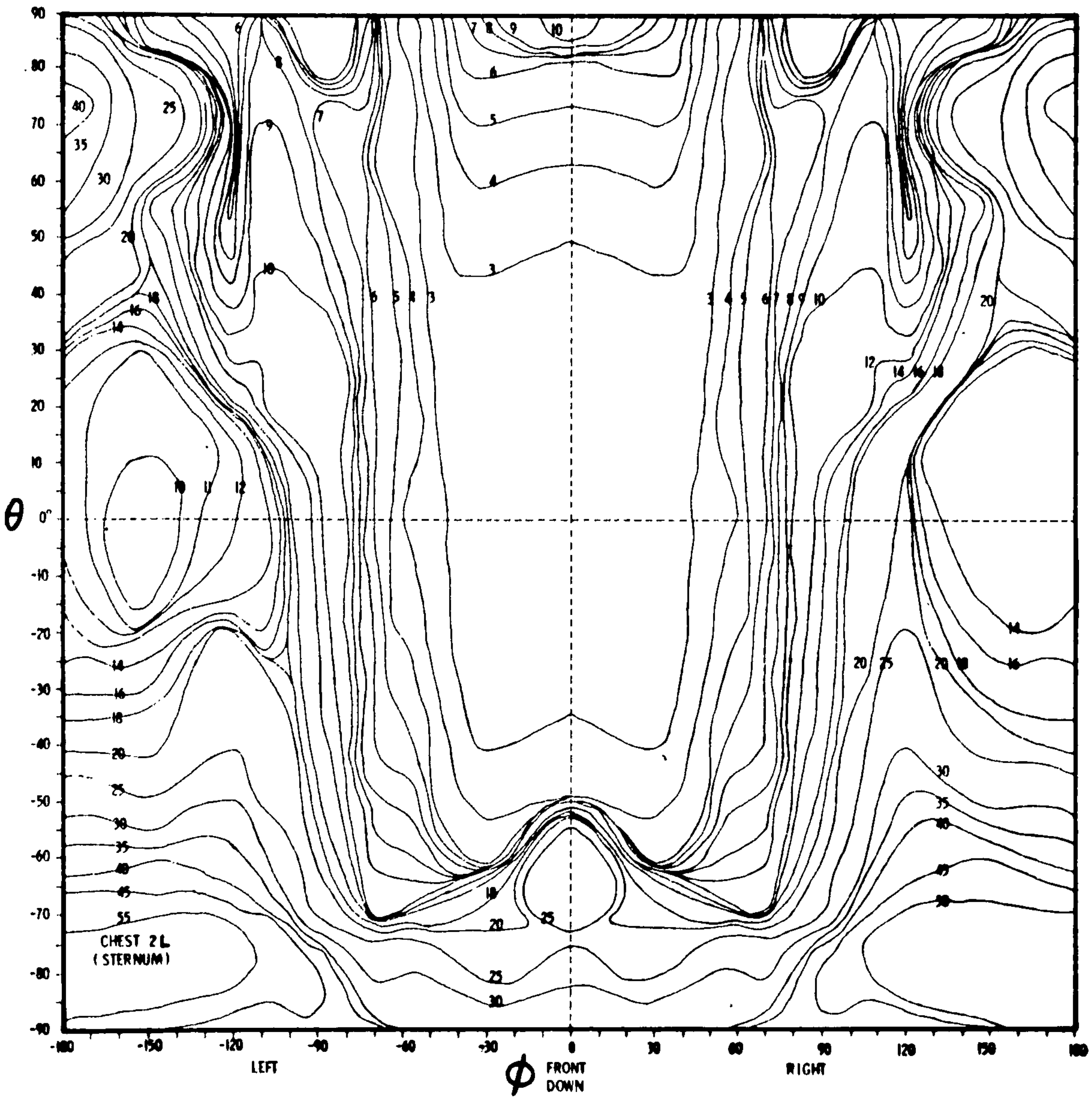

FIGURE 4. Contour plot of tissue isothicknesses in all directions about the point, CHEST 2, located as indicated in Table 1, in a seated 75-percentile man. $\theta = 0$, $\phi = 0$, center of figure, is the straight ahead horizontal direction.

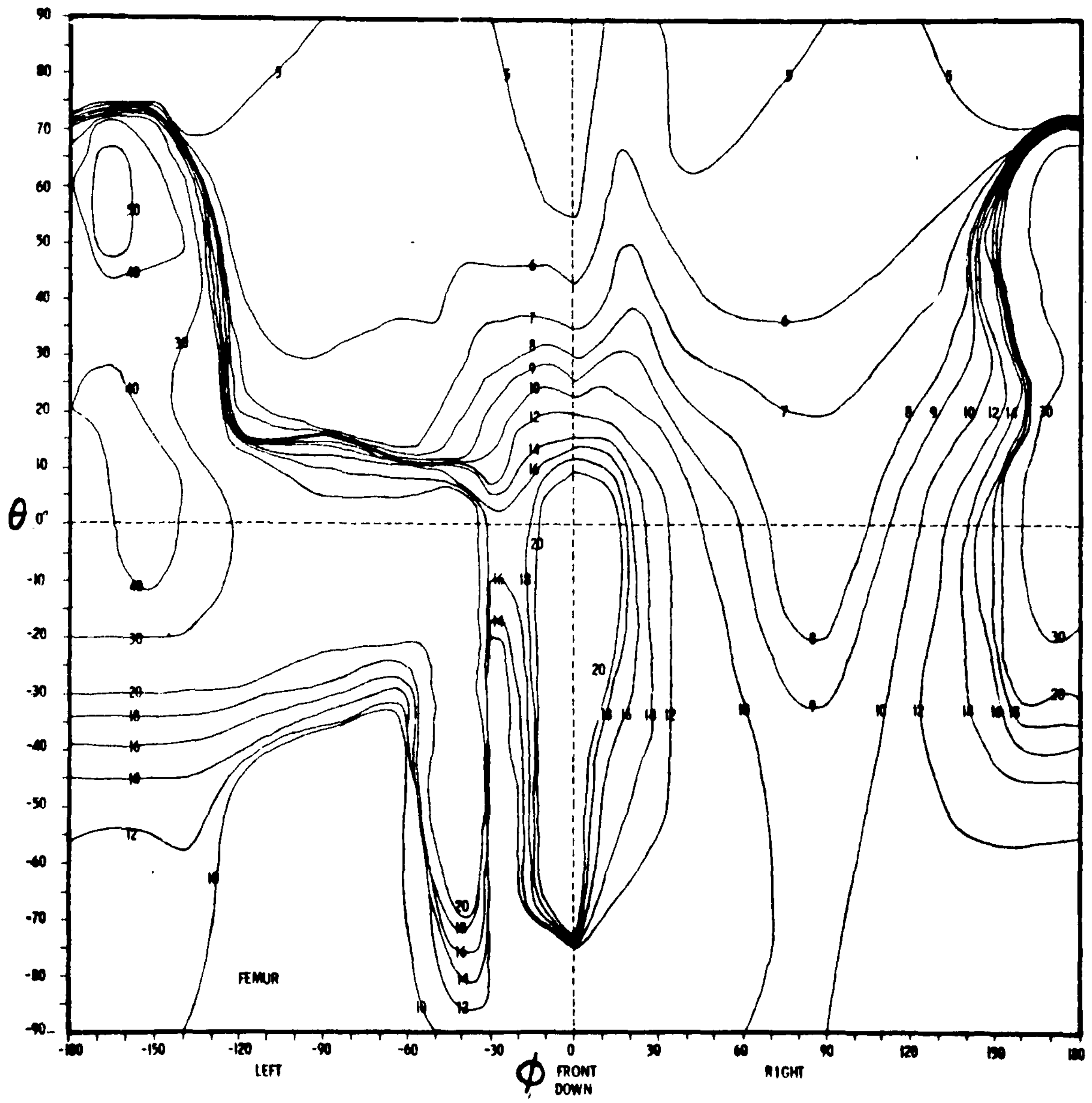

FIGURE 5. Conteur plot of tissue isothicknesses in all directions about the point, FEMUR, located as indicated in Table 1, in a seated 75-percentile man. $\theta = 0$, $\phi = 0$, center of the figure, is the straight ahead horizontal direction.

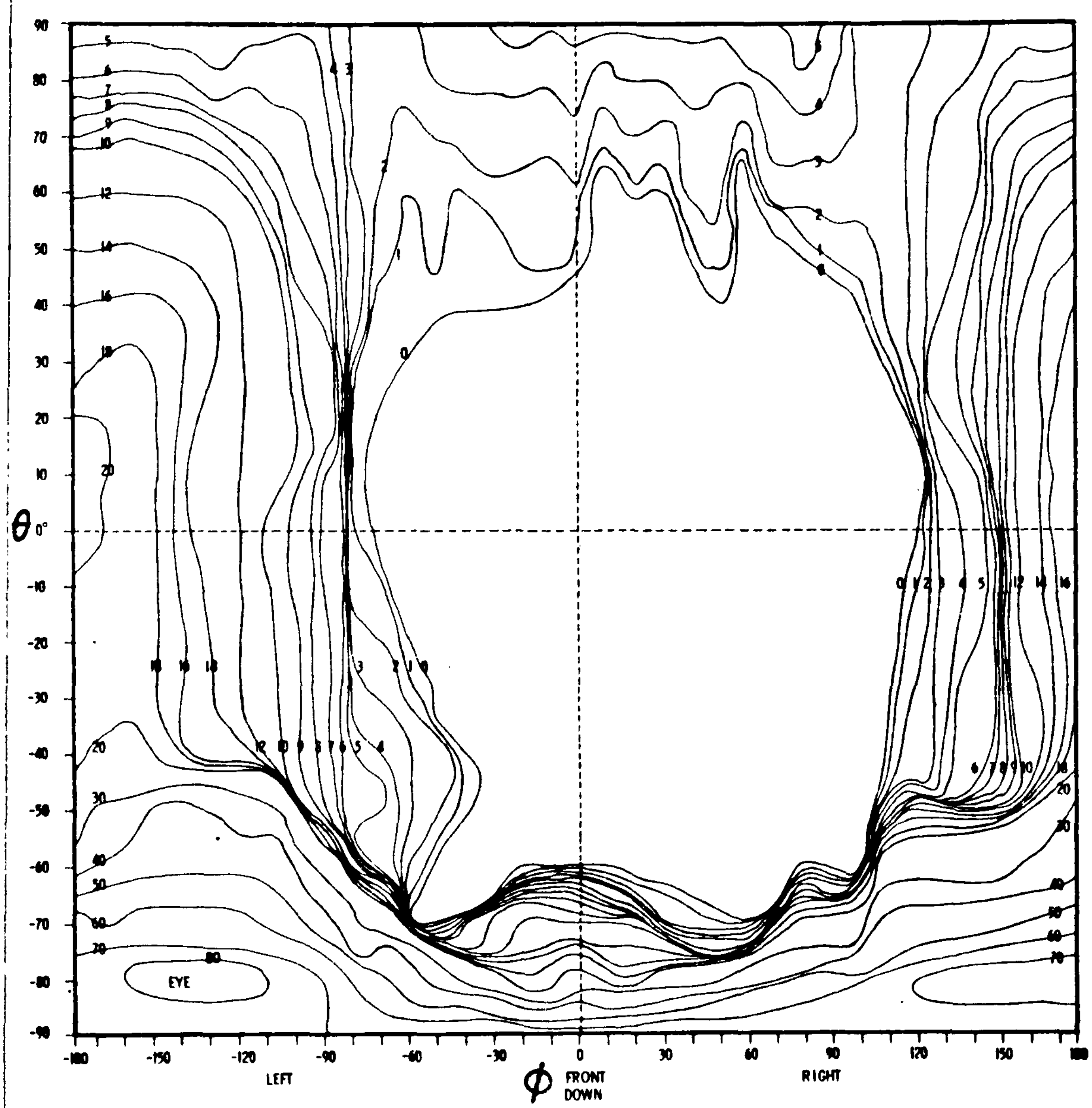

FIGURE 6. Contour plot of tissue isothicknesses in all directions about the point, EYE, located as indicated in Table 1, in a seated 75-percentile man. $\theta = 0$, $\phi = 0$, center of the figure, is the straight ahead horizontal direction.

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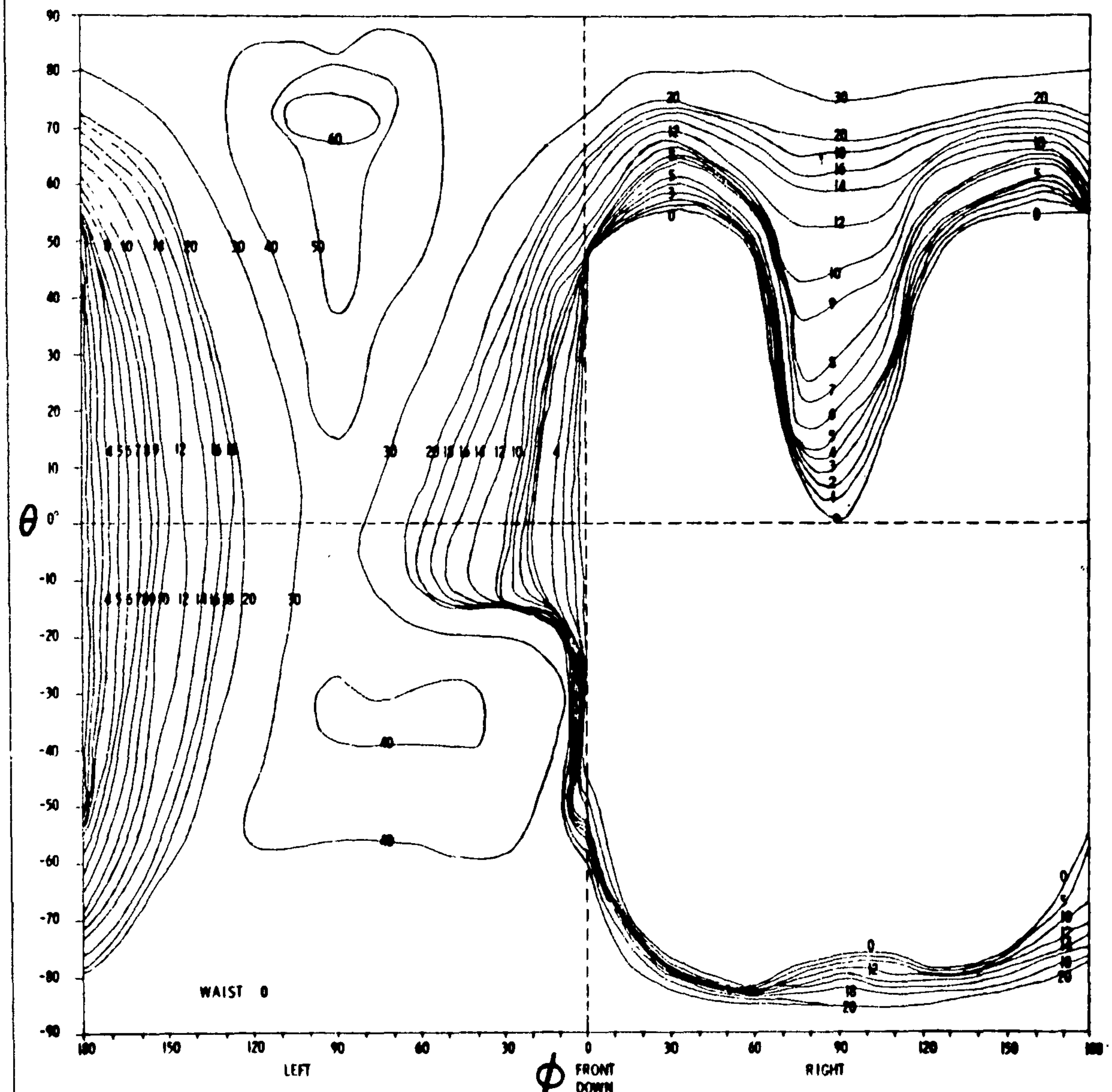

FIGURE 7. Contour plot of tissue isothicknesses in all directions about the point, WAIST 0, located as indicated in Table 1, in a seated 75-percentile man. $\theta = 0$, $\phi = 0$, center of the figure, is the straight ahead horizontal direction.

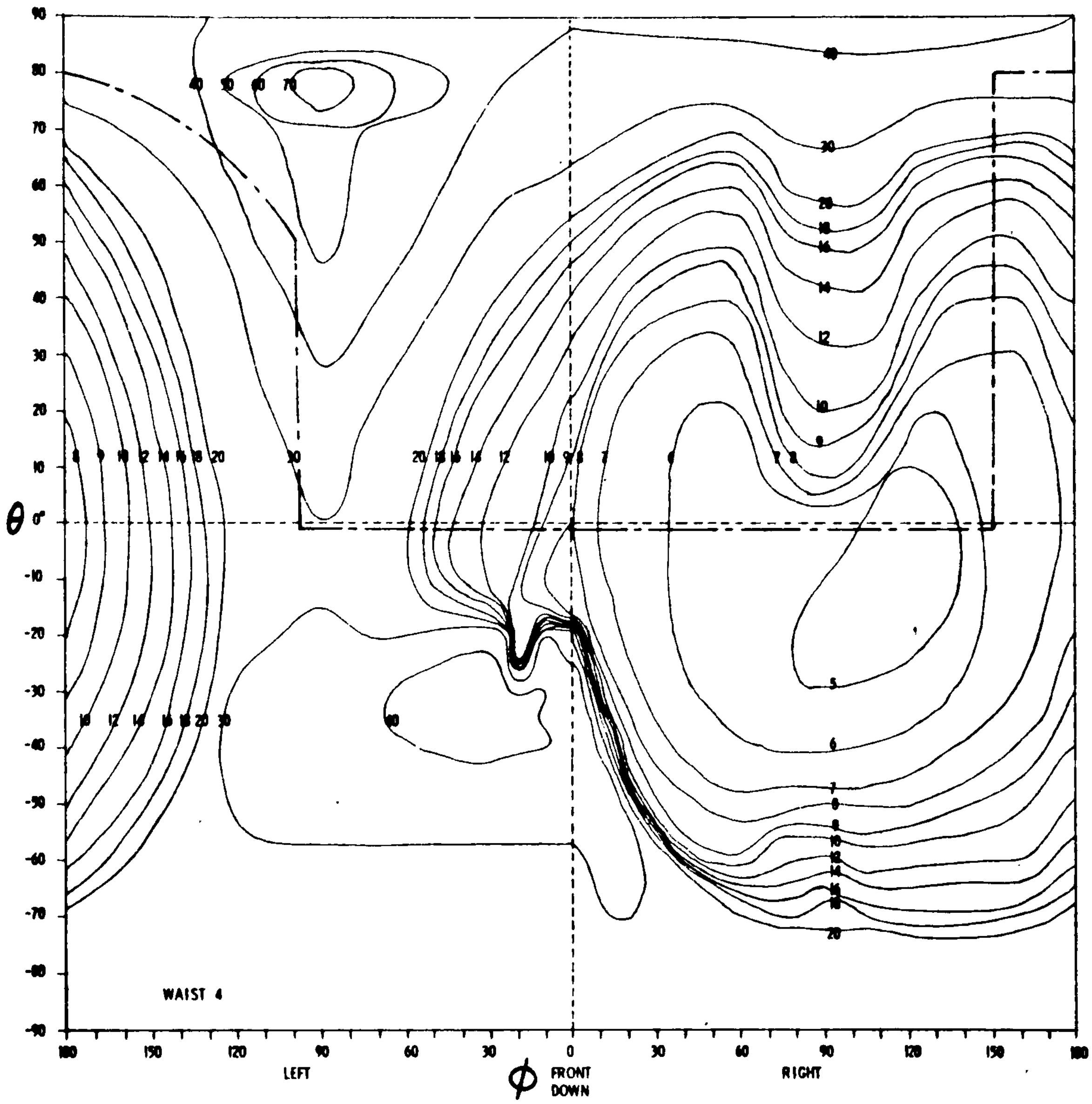

FIGURE 8. Contour plot of tissue isothicknesses in all directions about the point, WAIST 4, located as indicated in Table 1, in a seated 75-percentile man. $\theta = 0$, $\phi = 0$, center of the figure, is the straight ahead horizontal direction. — - — line shows the outline of the shielded chair assumed for the case WAIST 4S.

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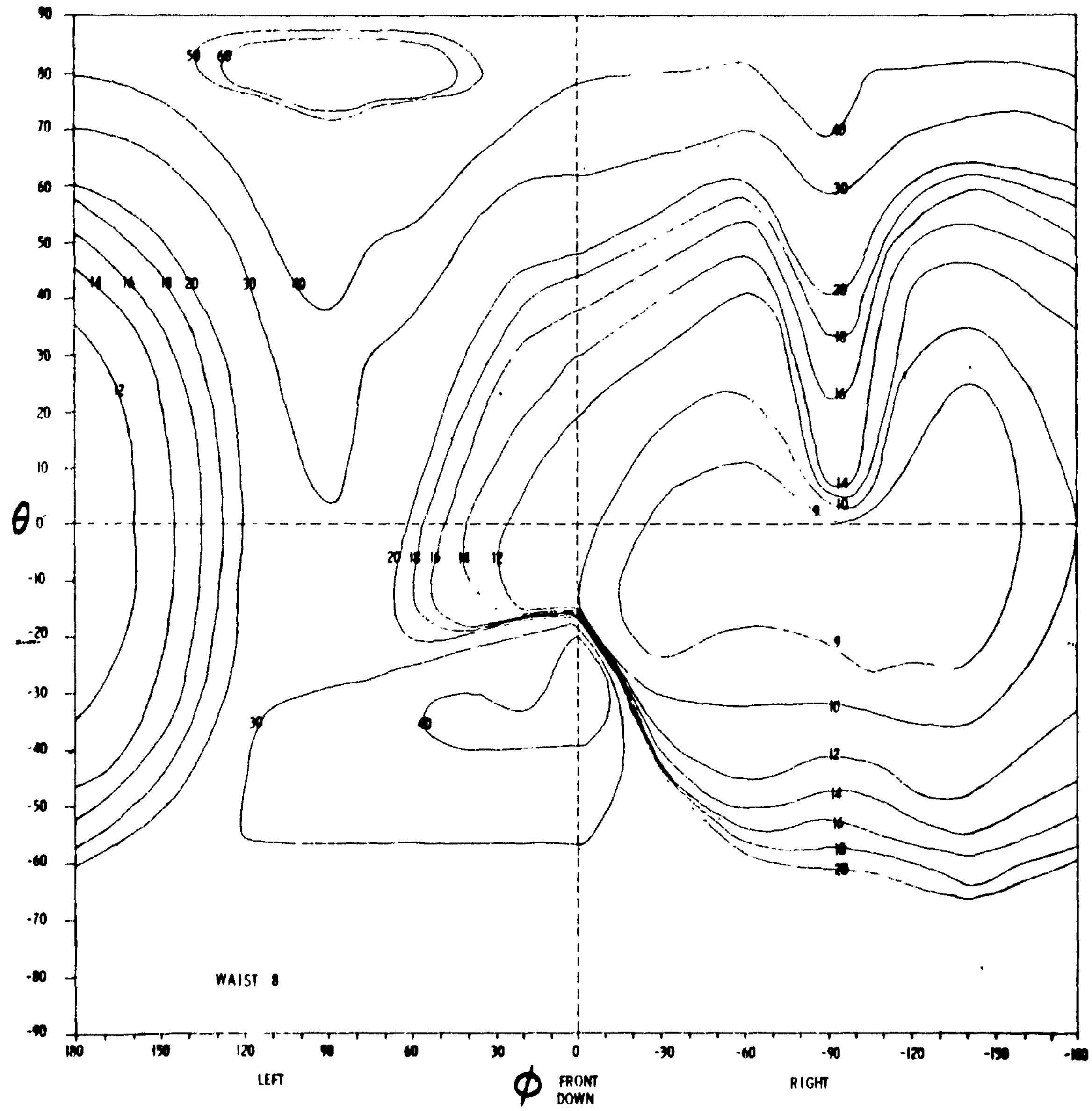

FIGURE 9. Contour plot of tissue isothicknesses in all directions about the point, WAIST 8, located as indicated in Table 1, in a seated 75-percentile man. $\theta = 0$, $\phi = 0$, center of the figure, is the straight ahead horizontal direction.

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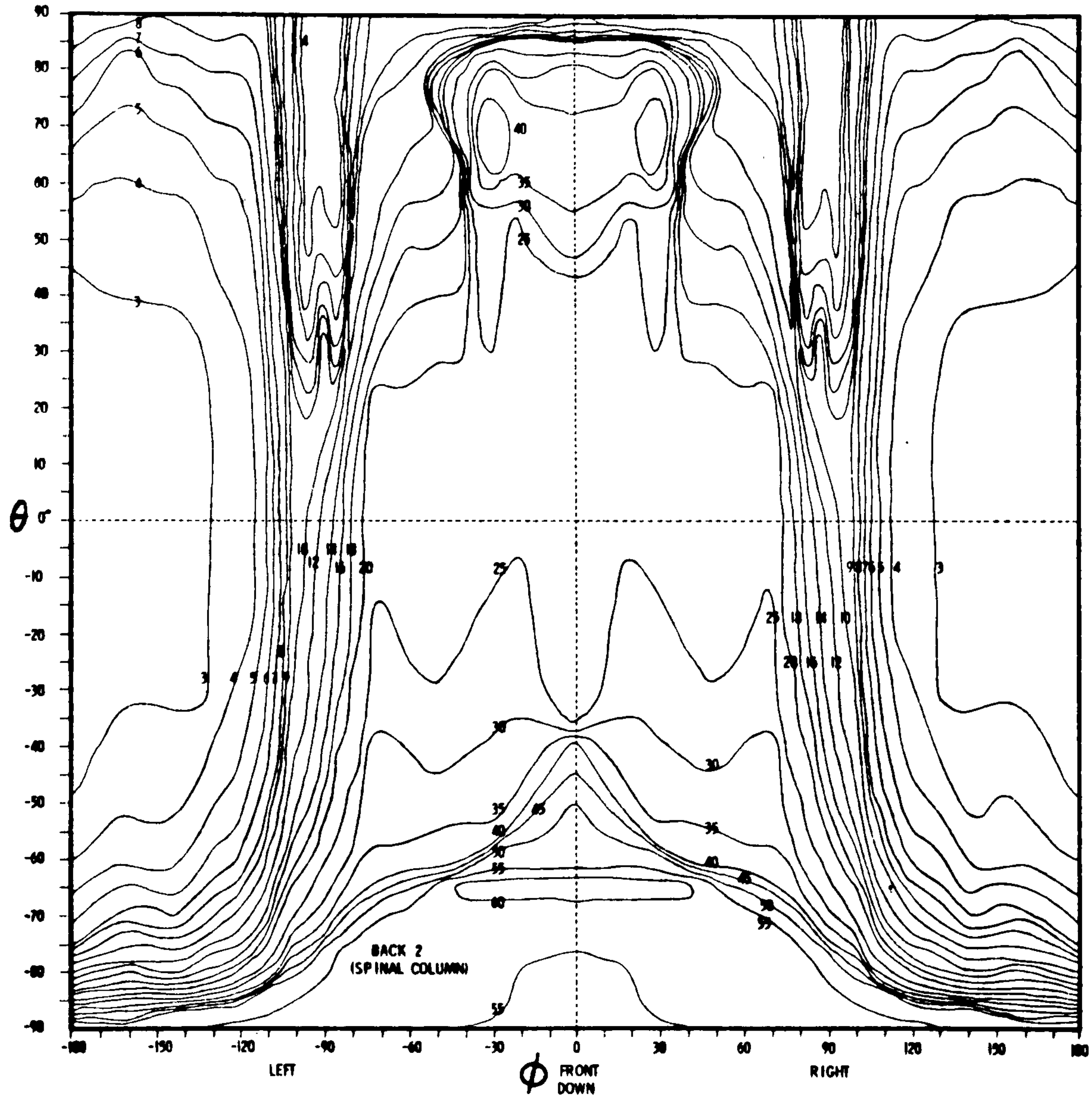

FIGURE 10. Contour plot of tissue isothicknesses in all directions about the point, BACK 2, located as indicated in Table 1, in a seated 75-percentile man. $\theta = 0$, $\phi = 0$, center of the figure, is the straight ahead horizontal direction.

USES OF ISOTHICKNESS CONTOURS

Whenever a human body is immersed in a known omnidirectional radiation flux, not necessarily isotropic, the amount of radiation reaching a specific body point and the dose absorbed there may be calculated using the isothickness contours if the absorption properties of the radiation are known. The motivating example for this study is the space radiation environment, but the contours given may be used with arbitrary angular distributions of any incident flux. Consider an angular distribution of some radiation incident upon the body, $F(\theta, \phi)\, d\Omega$, which is attenuated according to some functional expression $A(x)$ where x is the thickness of tissue. x in turn is a function of θ and ϕ, according to the isothickness contours; let this function be $x_p(\theta, \phi)$ corresponding to point P in the body. Further, let D be the conversion factor from flux to absorbed dose for the type and quality of the radiation; D need not be a constant, indeed it is generally dependent upon energy spectrum, which in turn depends upon x. The way in which dose is computed is not in the scope of this document.

Remembering that $d\Omega$ is $\cos\theta\, d\theta\, d\phi$, we can write the process of a dose computation in the following symbolism:

$$\text{Flux at P} = \iint \left[F(\theta, \phi)\right] \left[A(x_p(\theta, \phi))\right] \cos\theta \; d\theta \; d\phi,$$

$$\text{Dose at P} = \iint \left[F(\theta, \phi)\right] \left[A(x_p(\theta, \phi))\right] \left[D\right] \cos\theta \; d\theta \; d\phi,$$

where energy spectral dependences are implicitly contained in the bracketed terms.

A simple, but useful and illustrative case is afforded by the isotropic distribution $F(\theta, \phi)$ = constant. For this distribution one can perform the integrations by numerical approximation. The isothickness contours have

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been analyzed into fractional solid angle subtended by a series of thicknesses. Thus the fraction of the θ, ϕ sphere occupied by various thicknesses was determined graphically, with allowance made for the change in size of the area element $d\theta\ d\phi \cos\theta$ over the sphere. This was done by counting squares on the isothickness plots, the space between contour lines being assigned to an intermediate value of thickness. The space between contours was weighted by the $\cos\theta$ factor by counting squares within 5- or 10-degree wide latitude bands, and assigning the average latitude value. Thus, for the band 30 to 35 degrees the area between the 11 and 12 cm tissue thickness contours was multiplied by $\cos 32.5^\circ$ and assigned to the thickness 11.5 cm. This area was computed in units of the area of a sphere of unit area. Thus the total angular area of all thickness regions should add up to unity, providing a check of the graphical accuracy.

Because of the importance of the isotropic distribution, the results of the analysis of the isothickness contours for the twelve selected points are tabulated. In Table 2, column 1 gives a tissue thickness; columns 2 to 14 show the fractional solid angle subtended about the indicated body point in the 75-percentile seated man. For a given body point, using a set of these fractional solid angle values and respective thicknesses x, one may compute dose at that body point by the summation:

$$\text{Dose} = (F) \sum_i A(x_i)\ \Omega_i(x) \left[\text{Dose Conversion } (x_i)\right]$$

where F is incident isotropic flux on the body

$A(x_i)$ is the absorption in x_i cm of tissue,

$\Omega_i(x)$ is the fractional solid angle corresponding to x_i thickness,

$\left[\text{Dose Conversion } (x_i)\right]$ is the flux-to-dose relationship, here unspecified, but dependent upon x_i through its spectral dependence.

TABLE 2. Fractional Solid Angle for Various Tissue Thicknesses in the Seated Human at Various Body Points.

x (cm)	GUT	CHEST 0	CHEST 2	CHEST 2L	BACK 2	WAIST 0	WAIST 1	WAIST 4	WAIST 6	WAIST 8	FEMUR	EYE
0		0.5135				0.3977						0.4004
0.5		.0116				.0108						.0394
1.5		.0100				.0112						.0398
2.5		.0099	0.1758	0.1758	0.1705	.0120	0.1447					.0472
3.5		.0107	.0819	.0819	.1137	.0142	.1312					.0316
4.5		.0073	.0486	.0486	.0624	.0177	.0581	0.0372			0.0174	.0282
5.5		.0102	.0365	.0365	.0359	.0175	.0405	.0928			.1129	.0272
6.5		.0079	.0289	.0289	.0331	.0154	.0422	.1023	0.0405		.0754	.0219
7.5		.0085	.0308	.0308	.0241	.0161	.0283	.0661	.1103		.0707	.0201
8.5		.0075	.0243	.0241	.0192	.0198	.0315	.0524	.0707	0.1063	.0407	.0249
9.5		.0079	.0273	.0577	.0240	.0179	.0316	.0481	.0609	.0944	.1028	.0221
10	0.1700											
11	.0950	.0139	.0430	.1394	.0275	.0307	.0437	.0634	.0944	.1259	.1239	.0471
13	.1230	.0111	.0356	.1062	.0265	.0318	.0368	.0570	.0826	.0911	.0666	.0529
15	.0980	.0150	.0473	.0484	.0242	.0244	.0351	.0477	.0535	.0751	.0464	.0359
17	.1100	.0129	.0315	.0342	.0264	.0218	.0334	.0331	.0428	.0567	.0380	.0350
19	.1460	.0148	.0316	.0397	.0301	.0211	.0295	.0364	.0427	.0485	.0383	.0429
22.5	.0880	.1002	.1625	.0521	.2068							
25						.1304	.1213	.1704	.2212	.2230	.1610	.0281
27.5	.0450	.1105	.0766	.0416	.0731							
32.5		.0699	.0546	.0187	.0403							
35	.0560					.1293	.1293	.1383	.1328	.1247	.0784	.0149
37.5		.0189	.0185	.0131	.0227							
42.5		.0081	.0136	.0099	.0070							
45	.032					.0496	.0544	.0460	.0441	.0496	.0243	.0143
47.5		.0058	.0065	.0066	.0054							
55	.003	.0172	.0225	.0121	.0246	.0087	.0083	.0067	.0012	.0015	.0317	.0076
65					.0032	.0018	.0012	.0020	.0024	.0035		.0059
75	.002						.0004	.0008				.0044
80	.003											.0012

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MODIFICATION OF CONTOURS BY CONSIDERATION OF OTHER DETAILS

AIR IN THE LUNGS

The isothickness contours for CHEST 2L, the sternum with lung air considered, differ from those of CHEST 2, in which the lung geometry was neglected. Table 2 shows the effect of this difference, in a comparison of columns 4 and 5. In an actual dose computation, the difference between the two cases amounts to less than ten percent for typical space proton spectra and simplified vehicles (Ref. 1). For a different type of radiation, such as low energy X-rays produced by space electrons, the effect of neglecting the higher-Z bone absorption would override the lung air effect.

BONY COMPOSITION OF THE FEMUR

Instead of the simplified treatment of the femur (neglecting bone), it was decided also to compute the femur dose considering the fact that radiation has to traverse a compact bone cortex and a "spongy" bone (lamellar) interior structure to reach the marrow in bone center. This analysis was labelled "FEMUR B", and due to its complexity is not plotted here, but is rather tabulated in the appendix to this document. The isothickness contours for tissue and both bone types were plotted separately and superimposed to arrive at 72 separate thickness regions in the three-material contours. The somewhat predictable and fortunate result of the marrow dose calculations for FEMUR B was only a few percent less than that for the approximate FEMUR case, for space protons. The difference for X-rays would, however, be significant.

GENERAL CONCLUSIONS CONCERNING LUNGS AND BONES

The cases analyzed indicate that the extra effort involved in the human geometry problem to take account of bones and lungs is not justified for space proton dose computations, but is necessary for the calculation of space electron bremsstrahlung doses.

SUMMARY

A method has been described by which the human body tissue geometry, or any complex three-dimensional figure, may be analyzed into terms useful for calculations of radiation dosage to interior points. The method was applied to the seated human male (75-percentile U.S. Air Force man), to determine contours of constant tissue thickness about twelve radiologically interesting body points. For use in an isotropic radiation flux, the fractional solid angle subtended by various tissue thicknesses is given. The power of this approach is evident, for it replaces a complicated geometry problem with a (perhaps large) set of simple "straight-through" layered-shield problems. Each simple dose problem may be solved easily by electronic computer and the results weighted with the corresponding fractional solid angles and summed to arrive at the total dose at a point in the complicated geometry.

REFERENCES

1. Dye, D. L., "Space Proton Doses at Points Within the Human Body," The Boeing Company, Document D2-90106.

2. Hertzberg, Daniels, and Churchill, "Anthropometry of Flying Personnel-1950," Wright Air Development Center, Technical Report 52-321, 1954.

3. Morton, D., ed., _A Manual of Human Cross Sectional Anatomy_, Williams and Wilkerson Publishing Co., 19[illegible].

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APPENDIX A

FEMUR B

Here are tabulated the fractional solid angles for various thicknesses of tissue and bone around a point in the femur 38 cm forward of the seat back and 9 cm up from the seat. Two types of bone were considered, a compact bone cortex, and a spongy (lamellar) bone interior, of density 1.85 and 1.17 g/cm^3, respectively. This tabulation is a somewhat more exact analysis of the femur than that listed in Table 2 in the text. There, the body was assumed to be entirely composed of 1 g/cm^3 density tissue. Column 1 of Table A-1 lists various thicknesses of spongy bone about the selected point in the various directions. Column 2 lists, for each value of column 1, thicknesses of compact bone. In columns 3 to 12 are listed, for each bone thickness set, the fractional solid angle corresponding to the thicknesses of tissue given at the heads of the columns. All thicknesses are given in g/cm^2 units.

WAIST 4S

An analysis was made of the effect of a shielded chair on which an astronaut might be sitting while being exposed to radiation. In Table A-2 are given the fractional solid angles for the case of the 4 cm depth in the waist (25 cm above seat, 4 cm in from right side). The outline of the chair as seen from this point is indicated by the dashed line in Fig. 8 . Besides providing seat and thigh shielding, it covers the back, wraps around the sides to a height of 25 cm above the seat level, and has a 10 cm wide belt around the abdomen 15 to 25 cm above the seat level. The thickness of the shielding chair may be any desired value and is given

TABLE A-1. Solid Angles for the FEMUR B Case. (Percent)

Bone		Tissue (g/cm^2)									
Spongy (g/cm^2)	Compact (g/cm^2)	4.5	5.5	6.5	7.5	8.5	9.5	12.5	17.5	25	40
1.17	0.925	15.671	6.010	2.222	7.986	0.679	0.346	0.745	1.510	2.479	0.859
1.17	1.388				1.360	0.288	0.202		1.357		
1.462	0.925	3.627	6.239	2.930	2.488	2.925	0.618	0.486	0.607	1.757	1.396
1.462	1.388		0.394	0.499	0.676	0.224	0.406	0.495	2.770		1.420
2.045	0.925		0.718	0.986	0.589	0.817	1.622	0.681			
2.045	1.388		0.216	0.557	0.478	0.692	1.463	1.119	1.432	1.199	2.138
2.045	2.313					0.250		0.417			
2.925	1.388			0.418	0.260	0.328	0.490	0.754	0.480	0.232	
2.925	2.313				0.466		0.462	0.387	0.478	0.561	0.877
2.925	3.238							0.644	0.458	0.540	
4.680	2.313										0.589
4.680	3.238							0.670		0.736	
4.680	4.625						0.489		0.985	0.360	
8.77	4.625									0.710	

TABLE A-2. Solid Angles for the WAIST 4S Case. (Percent)

Chair Thickness (g/cm^2)	Tissue Thickness (g/cm^2)	Fractional Solid Angle (percent)
0	4.5	0.648
0	5.5	2.723
0	6.5	3.935
0	7.5	2.663
0	8.5	1.712
0	9.5	1.549
0	11	3.135
0	13	3.880
0	15	2.159
0	17	1.166
0	19	1.246
0	25	4.580
0	35	4.612
0	45	2.685
0	55	0.669
0	65	0.200
0	75	0.075
x_{SH}	4.5	3.076
x_{SH}	5.5	6.557
x_{SH}	6.5	6.295
x_{SH}	7.5	3.947
x_{SH}	8.5	3.528
x_{SH}	9.5	3.256
x_{SH}	11	3.205
x_{SH}	13	1.816
x_{SH}	15	2.611
x_{SH}	17	2.148
x_{SH}	19	2.398
x_{SH}	25	12.460
x_{SH}	35	9.218
x_{SH}	45	1.915
	Total	100.337

as x_{SH} in Table A-2. In the cases analyzed for actual space proton dose calculation, 2 g/cm^2 and 4 g/cm^2 polyethylene thickness were chosen as typical feasible chair shielding values. These dose computations are reported elsewhere (Ref. 1), and show the effect of the chair shielding on the WAIST 4 point total dose (primary plus secondary) to be noticeable but probably not significant from the protection point of view.

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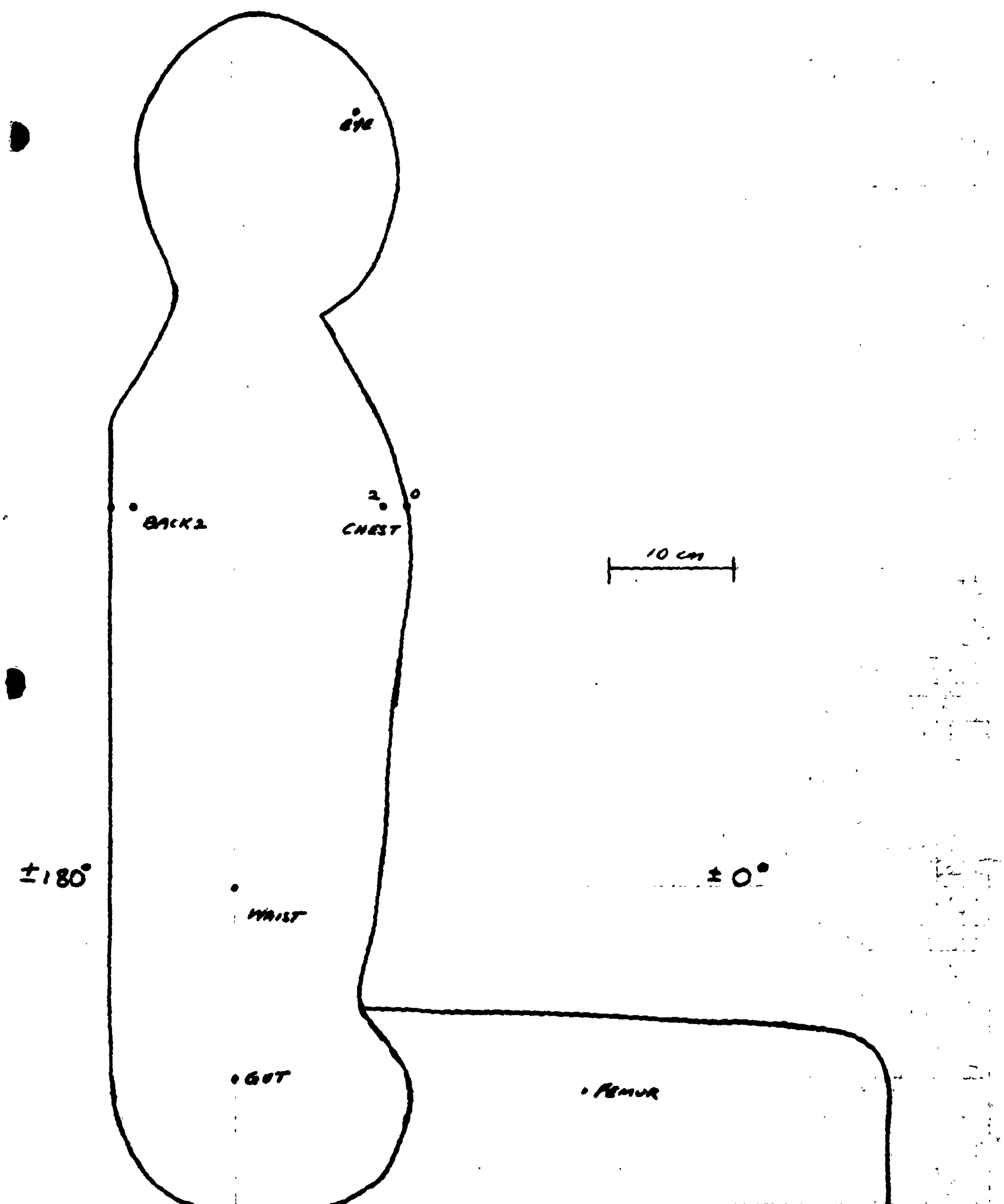
APPENDIX B

Here are given some of the basic outline and section drawings of the seated 75-percentile male assumed for this study. (The lower leg drawings are not given here.) Table B-1 gives the data from the Hertzberg, Daniels, and Churchill report (Ref. 2) used in making these scale drawings of the human body.

In Fig. B-1 a side view is shown, drawn from the data of Table B-1, but not showing the lower legs. In Fig. B-2 the back view is shown, less lower legs. In Fig. B-3 the top view is given, with transverse sections drawn at indicated heights above the seat level. The selected analysis points are indicated on Figs. B-1 and B-2. Figures B-4 and B-5 show the transverse sections of the head, based on the data of Table B-1, the views given in Morton's Human Cross Sectional Anatomy (Ref. 3), and some artistic imagination. Figures B-6 and B-7 show side and front views of the head, respectively, as used in the isothickness contour mapping of the eye.

TABLE B-1. Measurements on Seated 75-Percentile Man.

	Distance (cm)
Seat level to top of head	93.6
" " " eye	82.2
" " " shoulder	61.0
" " " waist	24.8
" " " thigh clearance	15.2
" " " bottom of feet (popliteal height)	44.5
Knee level to bottom of feet (knee height)	56.8
Chest depth (A - P distance)	24.3
Waist depth (A - P distance)	21.6
Buttock depth (A - P distance)	23.8
Buttock (back of seat) to knee length	61.8
Chest breadth (lateral)	31.9
Biacromial diameter	41.1
Bideltoid diameter	47.0
Elbow-to-elbow breadth	46.3
Hip breadth	37.0
Knee-to-knee breadth	20.9
Head length (forehead-to-chin)	19.3
Head depth	20.1
Head breadth	31.9



CALC			REVISED	DATE	SIDE VIEW	
CHECK						D2 90107
APR						Fig. B-1
APR					BOEING AIRPLANE COMPANY	PAGE 32
	0.1" = 10 cm					

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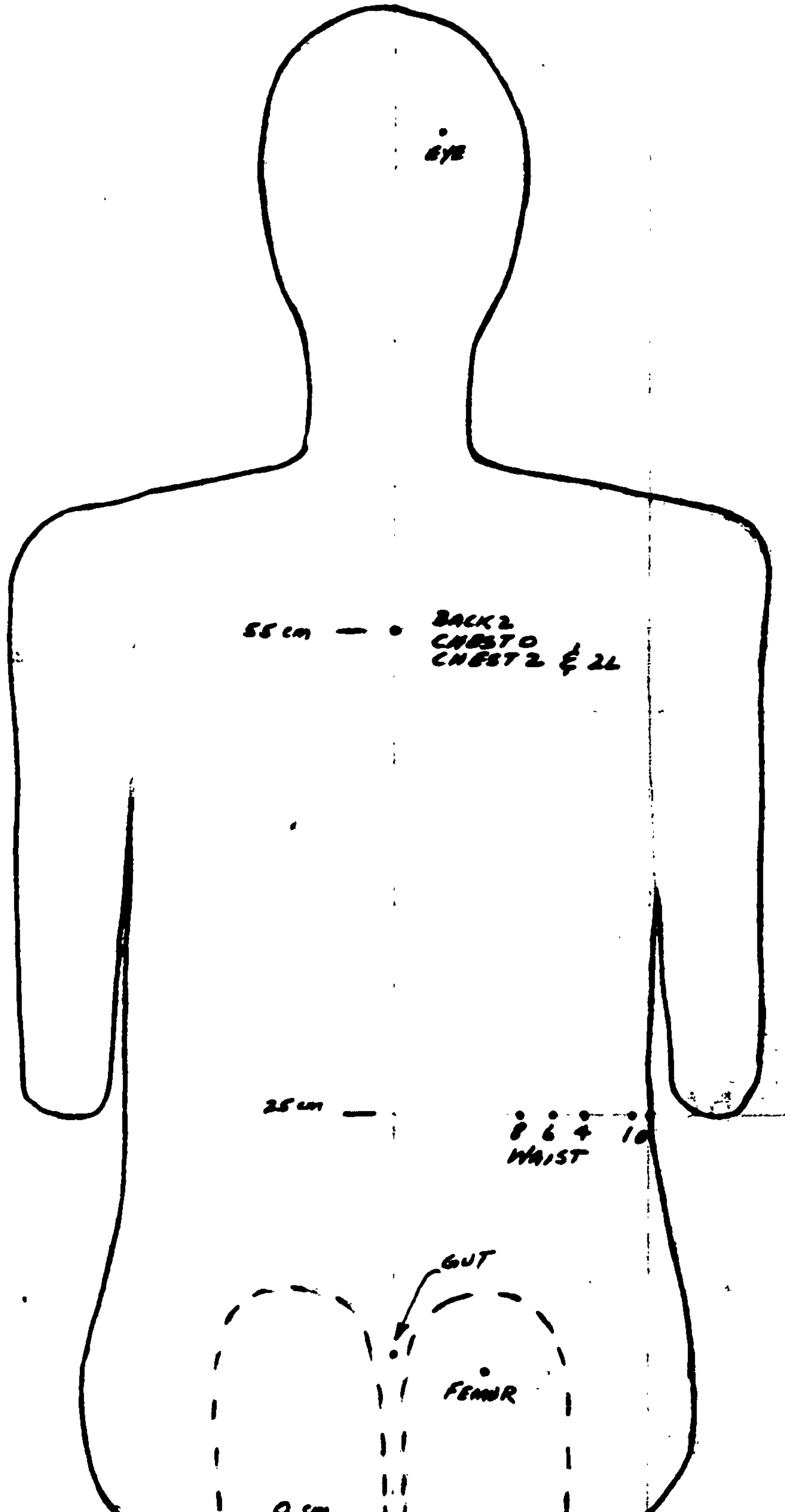

CALC			REVISED	DATE	BACK VIEW - SITTING	
CHECK						D290107 Fig. B-2
APR						
APR					BOEING AIRPLANE COMPANY	PAGE 33
	0.1" = 1 cm					

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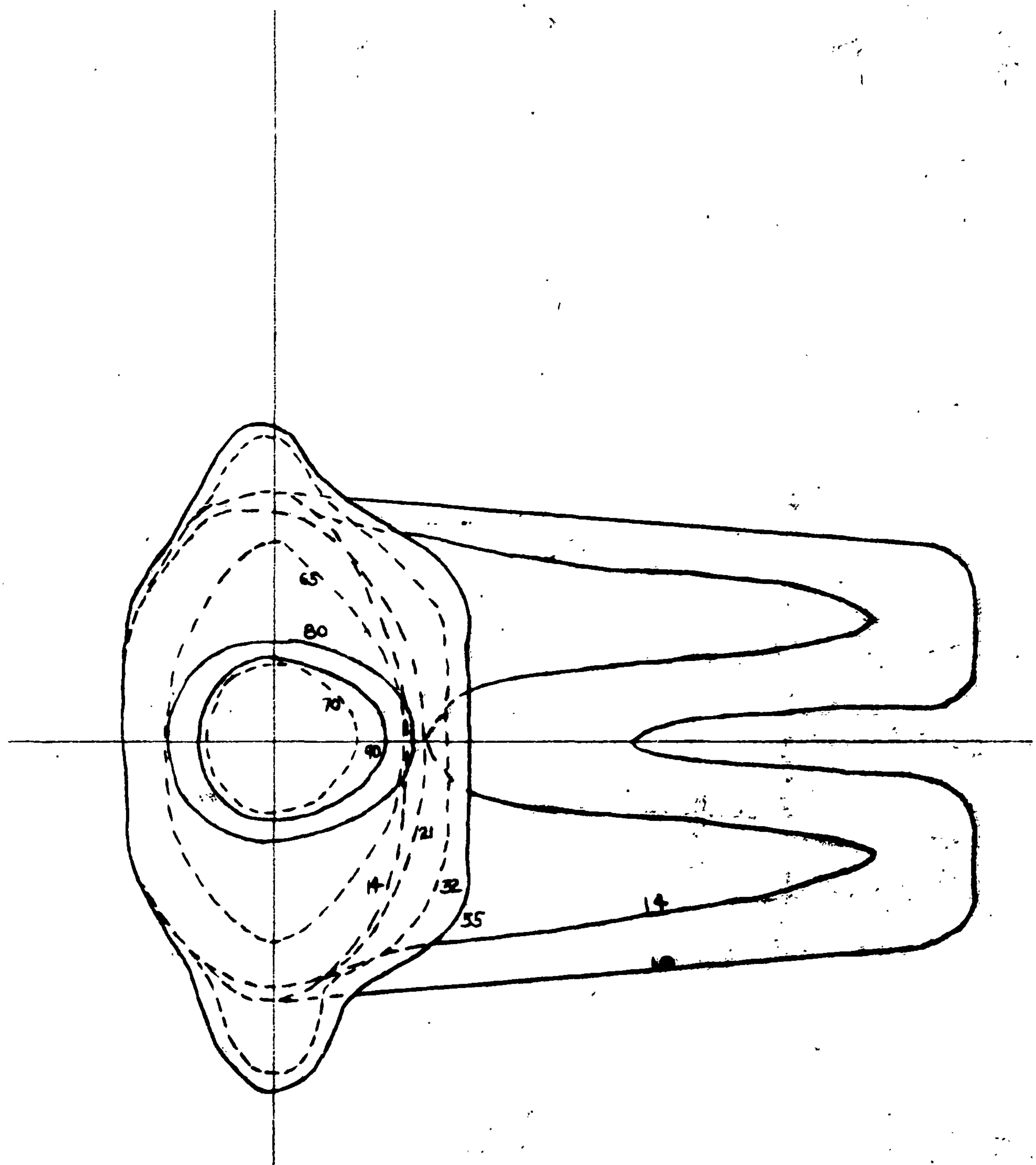
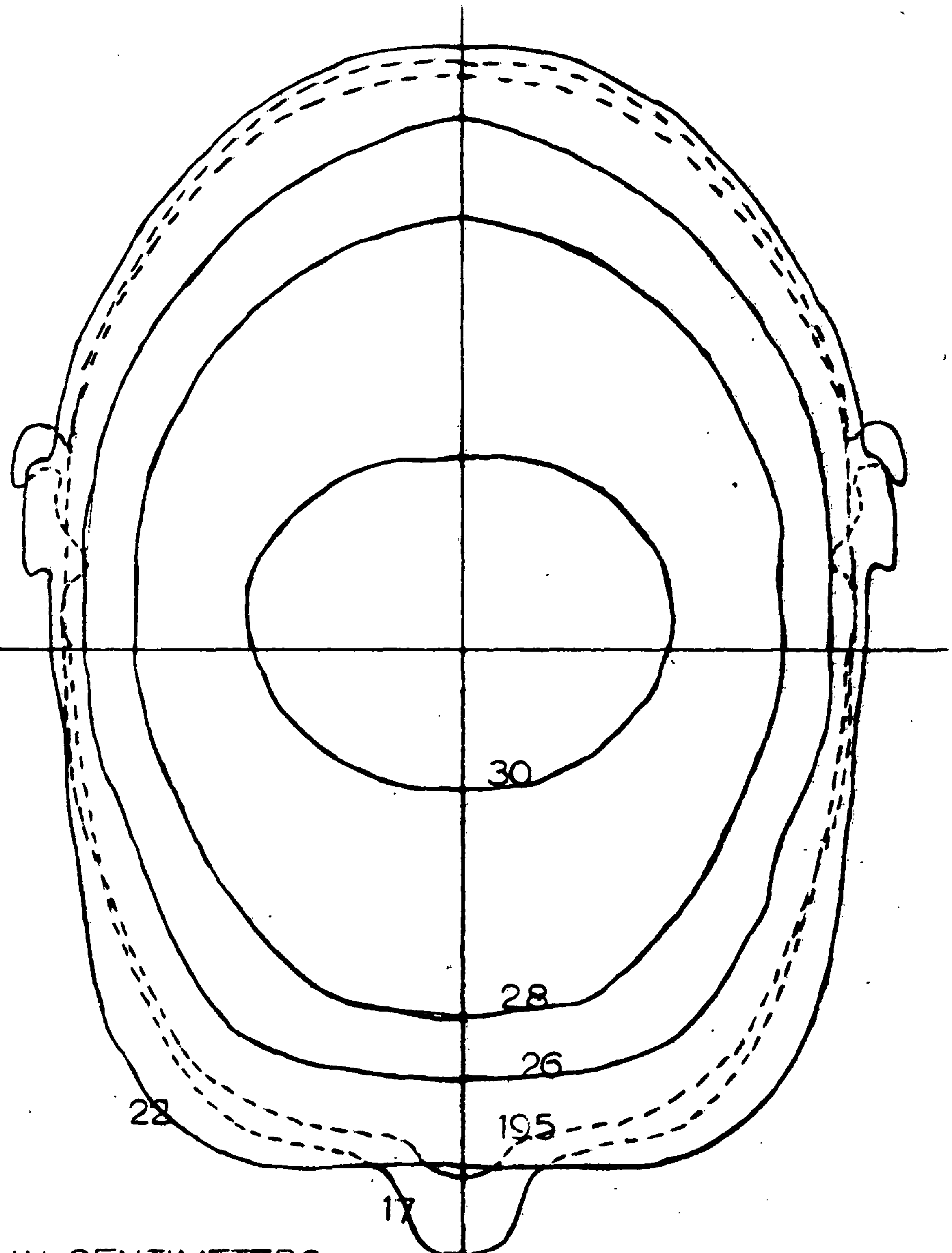


CALC	BJP	11-6	REVISED	DATE	HUMAN BODY TOP VIEW	
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE
	0.1"=1cm					

U3 4038 8000

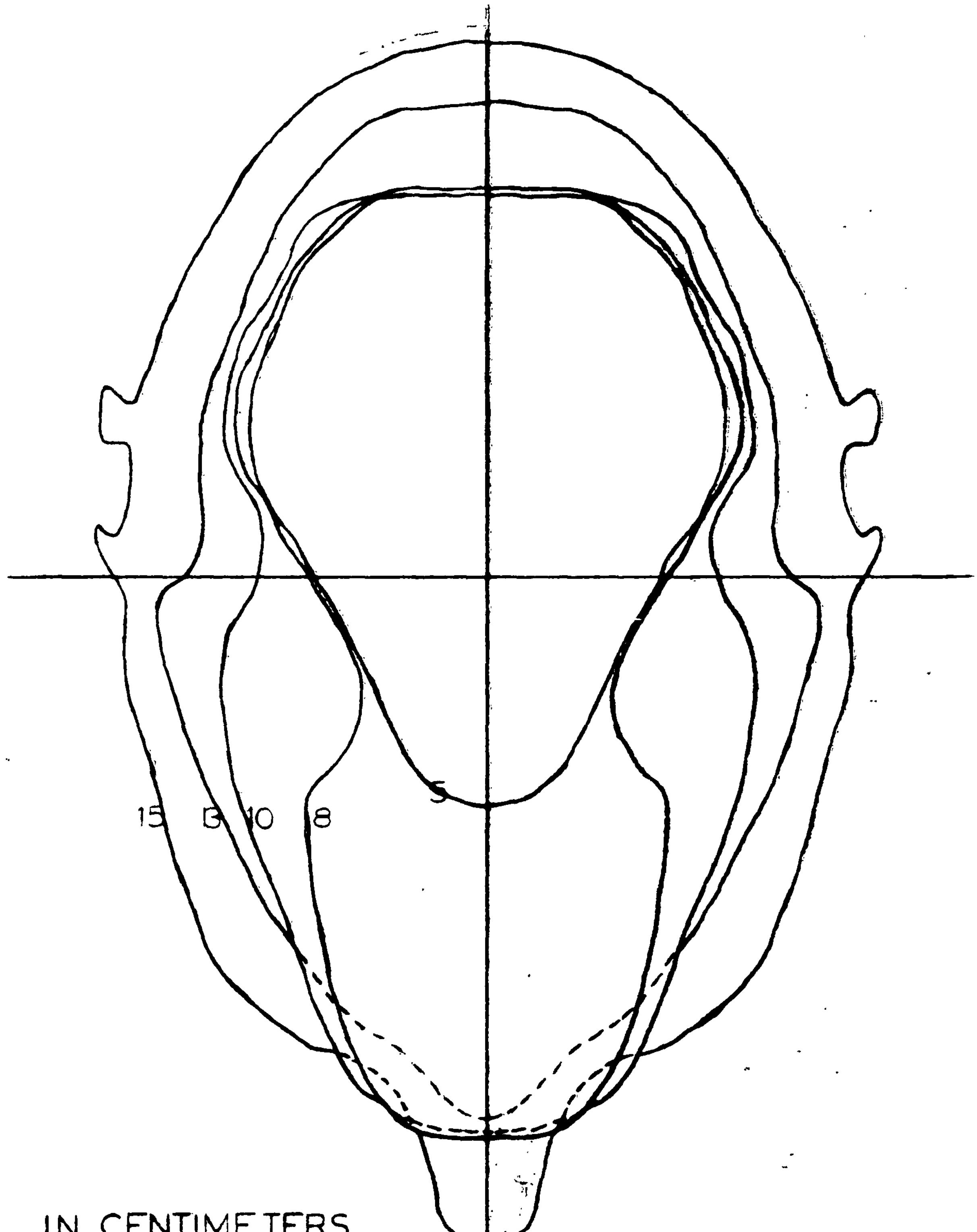


IN CENTIMETERS

CALC	BJP	11-8	REVISED	DATE	HUMAN HEAD 75%ILE	
CHECK					TOP VIEW TO NOSE	D2 9ar07 Fig. A4
APR						
APR					BOEING AIRPLANE COMPANY	PAGE 35
	FULL					

U3 4038 8000 (WAS BAC 1017 RS)

2-7000



IN CENTIMETERS

CALC	BJP	11-8	REVISED	DATE	HUMAN HEAD 75%ILE	
CHECK					BOTTOM VIEW TO NOSE	D2-90107 Fig. 8-5
APR						
APR					BOEING AIRPLANE COMPANY	PAGE 36
	FULL					

U3 4038 8000 (WAS BAC 1017 R5) 2-7000

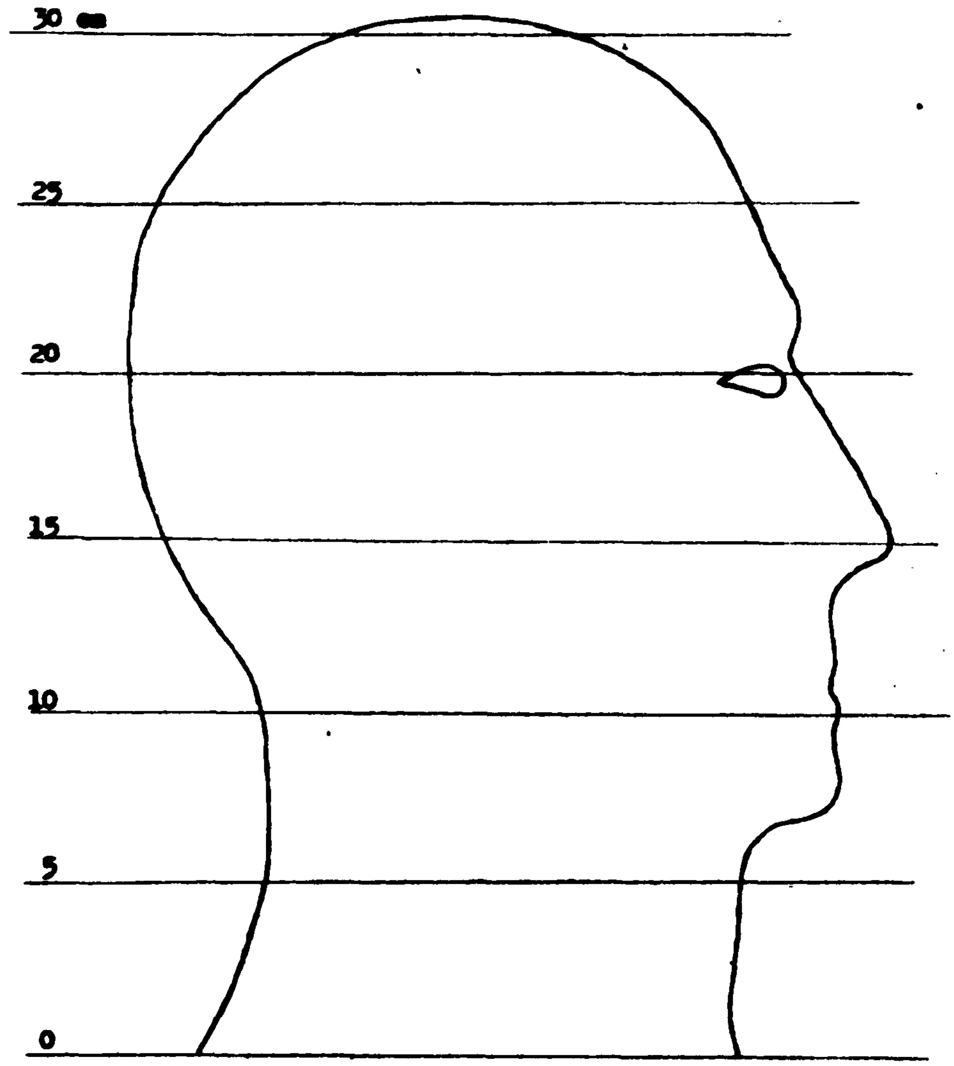


FIGURE B-6. Human head, side view.

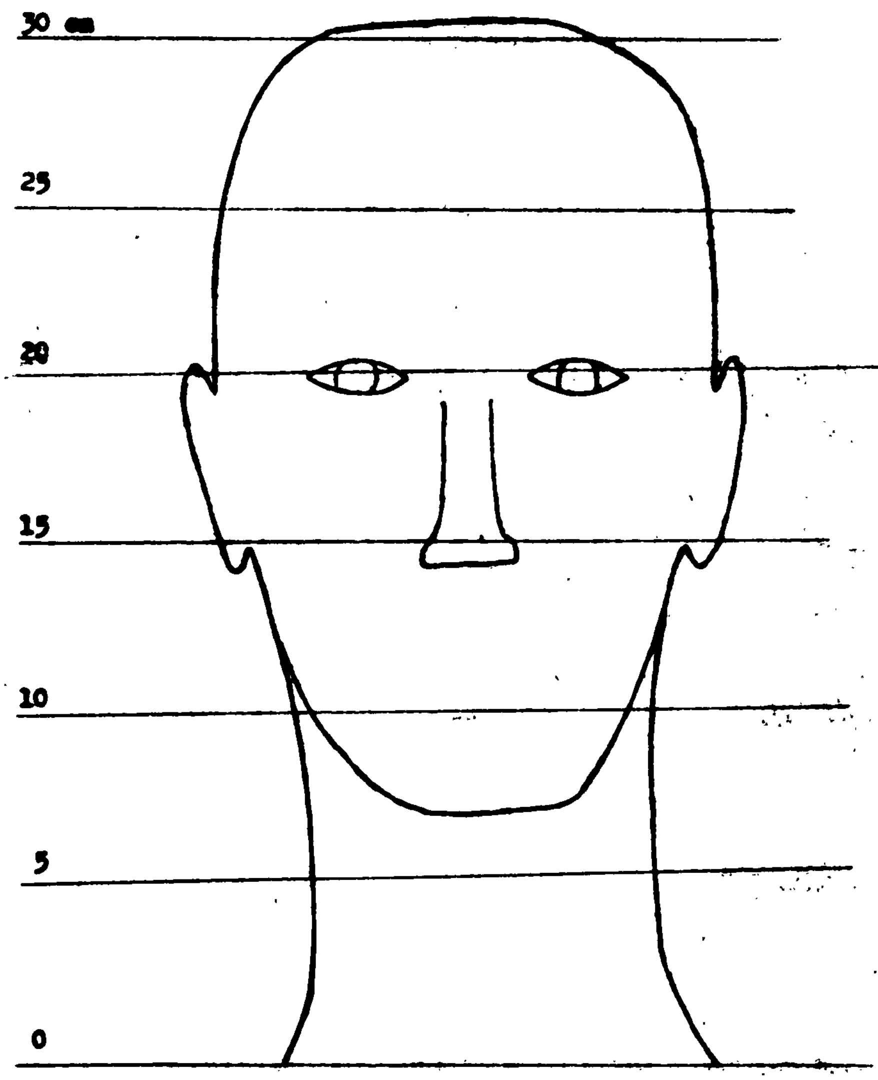


FIGURE D-7. Human head, front view.